Comparative Study of Mass Transfer in Wet and Dry Osmotic Dehydration

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Abstract

The differences in the external osmotic medium, dry or dissolved osmotic agent and its concentration (constant or variable) can significantly influence the kinetics of mass transfer. The objective of this work was to compare water and solute transport during the osmotic dehydration of strawberry pieces under different external conditions, wet or dry osmotic agent, with varying types of sugar (sucrose, fructose and isomaltulose). The evolution of the liquid phase concentration as well as the net fluxes under the different scenarios was described and modelled. Results showed that mass transfer kinetics were higher when the concentration of the external medium was variable, in the wet process slightly superior than in the dry process.

Keywords

Isomaltulose; Fructose; Sucrose; Mass Transfer; Osmotic Dehydration; Strawberry

Introduction

Many studies focused on the influence of the different variables on mass transfer kinetics during osmotic dehydration of fruits can be found in the literature. In most cases, the studies have analysed the influence of product variables (cultivar, variety, size, shape, etc.), osmotic solution, fruit: solution ratio, type of osmotic agent, agitation of the medium, etc. (Pani et al., 2008; Nieto et al., 2004; Lazarides, et al., 1999; Maestrelli, 1997; Fito & Pastor, 1994; Lerici et al., 1985; Pointing, 1973). The osmotic agents commonly used in osmotic dehydration of fruits are concentrated sugar solutions, and the kinetic studies of mass transfer are performed under internal control conditions, that is, by using solution-fruit ratios large enough to assume that the concentration of the external solution remains constant during dehydration. Under these conditions, internal control of water and soluble solid migration between the two phases, fruit and external solution, is ensured, easily permitting the estimation of the effective diffusivity from Fick's second law. Nevertheless, a large amount of solution is absent in industrial applications due to environmental sustainability, management and operating costs. In some cases, the osmotic solution is replaced by the use of a dry osmotic agent as in the case of meat and fish salting, in which it is very common to use dry salt in what is called the dry salting process. Some differences have been found between wet and dry salting of cod for instance. The wet process using brines favours salt uptake, while the dry process maximizes dehydration or water outflow (Andrés et al., 2005; Barat et al., 2004). Although in both cases, the same concentration of salt can be reached in the final product, the operation yield and the texture of the salted product strongly depend on the salting method.

However, the use of solid sugar instead of osmotic solution for the osmotic dehydration of fruits has not been previously described. The direct contact between the fruit and the surrounding solid sugar provokes a water output which gradually dissolves the sugar generating a supersaturated solution which will be diluted as dehydration and the diffusion of sugar to the fruit progresses. The differences in the external osmotic medium (dry or dissolved and constant or variable concentration) can significantly influence either the kinetics of mass transfer or the magnitude of net fluxes of water and solutes.

Sucrose has been commonly used for the osmotic dehydration of fruit (Heredia et al., 2010, Heredia et al., 2009; Lombard et al., 2008; Seguí et al., 2008; Giraldo et al., 2003; García et al., 2002; Shi et al., 1995). Nevertheless, it presents some disadvantages from the point of view of human health such as their high glycemic and cariogenic indexes (Pereira et al., 2005;

Zengo & Mandel, 1972; Weidenhagen & Lorenz 1957). Hence, sucrose replacement by fructose and isomaltulose for instance, increasingly becomes interesting in the acquisition of new healthier products by means of osmotic dehydration.

On the one hand, fructose has a lower glycemic index but higher sweetener index than sucrose and glucose (Martínez&García, 2001). Moreover, it is important to point out that isomaltulose, a sugar obtained from sucrose by means of a transglucosilation reaction (Schiweck et al., 1990), characterized with one of the lowest glycemic and cariogenic indexes among sugars is especially suitable for diabetic patients, children and sports people (Jeffery et al., 2006; Pereira et al., 2005; Pawlak et al., 2004; Lina, Jonker & Kozianowski et al., 2002; Matsuyama et al., 1997). Nevertheless, isomaltulose presents some technical handicaps such as 30% lower solubility and half the sweetness of sucrose (Schiweck et al., 1990; Kaga & Mizutani, 1985).

Hence, partial or total replacement of sucrose by fructose and/or isomaltulose as the osmotic agent in solution or solid state could provide the industry with new possibilities to develop healthier products by means of osmotic dehydration.

The aim of this study was to compare water and solute transport during the osmotic dehydration of strawberry pieces under different external conditions, wet and dry osmotic agent, with different types of sugar (sucrose, fructose and isomaltulose), in all cases reaching the same equilibrium concentration.

Material and Methods

Raw Material

Strawberries (*Fragariavesca*) acquired in a local supermarket were sorted to eliminate damage fruits and homogenise the sample for colour, shape and ripening stage. Samples were immersed in chlorinated water to eliminate possible field residues, and were cut in quarters.

Methodology

Samples were equilibrated using three different processes: (1) Wet Osmotic Dehydration with Variable concentration of the medium (WOD-V): the osmotic medium used was a 60 Brix sugar solution (sucrose or fructose). (2) Wet Osmotic Dehydration with Constant concentration of the medium (WOD-C): the osmotic medium used was a 30 Brix sugar solution (sucrose, fructose or isomaltulose). (3) Dry Osmotic Dehydration with Variable concentration of the medium (DOD-V): the osmotic medium used was solid sugar (sucrose, fructose or isomaltulose).

All the experiments were carried out at 25 ºC. In the three processes, the fruit: solution ratio was estimated from the mass balance (equation 1) to assure a concentration of the fruit liquid phase of 30 Brix at equilibrium.

$$z_{eq} = \frac{m_0^S \cdot x_0^{ss} + m_0^{OS} \cdot y_0^{ss}}{m_0^S \cdot (x_0^{ss} + x_0^{w}) + \mathrm{m}_0^{\mathrm{OS}}} \qquad (1)$$

Where, z_{eq}: Concentration of the soluble solutes of the liquid phase at the equilibrium stage (g soluble solids/g liquid phase); m_0^s: Mass of strawberry at the beginning of the dehydration process (g strawberry); m_0^{OS}: Mass of the osmotic solution or solid sugar at the beginning of the dehydration process (g osmotic solution or g solid sugar); x_0^{ss}: Soluble solute concentration of the strawberry at the beginning of the dehydration process (g soluble solids/g strawberry); x_0^w: Water concentration of the strawberry at the beginning of the dehydration process (g water /g strawberry); y_0^{ss}: Soluble solute concentration of the osmotic solution or solid sugar at the beginning of the dehydration process (g soluble solids/g osmotic solution or solid sugar).

Strawberry quarters were placed in a plastic basket divided into compartments and immersed in a plastic vessel containing the osmotic solution or the solid sugar. At different predetermined times (0, 30, 60, 90, 120, 150, 180, 240, 300, 420, 540, 900, 1440 1740 and 2880 min), samples (quarters of strawberry) were removed from the osmotic solution, gently dried with absorbent paper and divided into three lots to perform the analytical determinations. Samples used for the control of mass variation were identified.

Physicochemic Alanalyses

All the physicochemical analyses were carried out in triplicate on fresh fruit, and at different times during the osmotic treatment.

For mass control as well as other physicochemical determinations, analytical balances with 0.0001 g precision were used. Moisture content was determined gravimetrically by drying to constant weight in a vacuum oven at 60ºC (method 20.103 AOAC, 1980). The content of soluble solids (Brix) was measured in previously homogenized samples with a refractometer

at 20ºC (ATAGO 3 T). For dehydrated samples, dilution was necessary at a ratio of 4 g water for each gram of sample for Brix measurements. Moisture and soluble solid content were expressed as mass fraction of water (x^w) and soluble solids (x^{ss}), respectively.

Results and Discussion

Evolution of the Liquid Phase Concentration

Figure 1 shows the theoretical typical evolution of the soluble solid concentration in the osmotic medium (y^{ss}) and in the liquid phase of the fruit (z^{ss}) under the different conditions described in the materials and methods section.

In the first case, WOD-V (Fig.1a), the liquid phase of the fruit becomes more concentrated due to the water out-flow by osmosis and to the diffusion of the solutes from the medium to the fruit as a consequence of the existing concentration gradient, while the external solution becomes more diluted as a consequence of the mentioned fluxes. The fruit: solution system reaches the equilibrium concentration when the concentration of the solution (y^{ss}) equals the concentration of the liquid phase of the fruit (z^{ss}) (Pointing, 1973), in this case 30 Brix since the fruit: solution ratio has been estimated to reach this target concentration.

When the volume of the external solution is large enough to assure that the concentration of the osmotic medium remains constant (WOD-C), the net fluxes of water and solutes only affect the concentration of the fruit liquid phase (Fig.1b). However, when the external medium is initially a solid sugar (DOD-V), the water from the fruit generates an external solution whose concentration changes in two stages (Fig.1c): (1) the oversaturation stage from the beginning until the sugar is completely dissolved and, (2) the variable concentration stage.

Figure 2 shows the results obtained in the equilibrium experiments using strawberry quarters under each of the situations previously described (Fig, 1). The results point out that the solubility of the different sugars (sucrose, fructose and isomaltulose) determines the duration of the oversaturation stage of the medium during dry osmotic dehydration processes. The duration of this step was 54, 55 and 120 minutes for sucrose, fructose and isomaltulose respectively. These times have been estimated from water loss data (taking into account the solubility of the different sugars) since the time required to extract the necessary amount of water to dissolve the total amount of sugar is equivalent to the processing time, during which the fruit is in contact with an oversaturated solution.

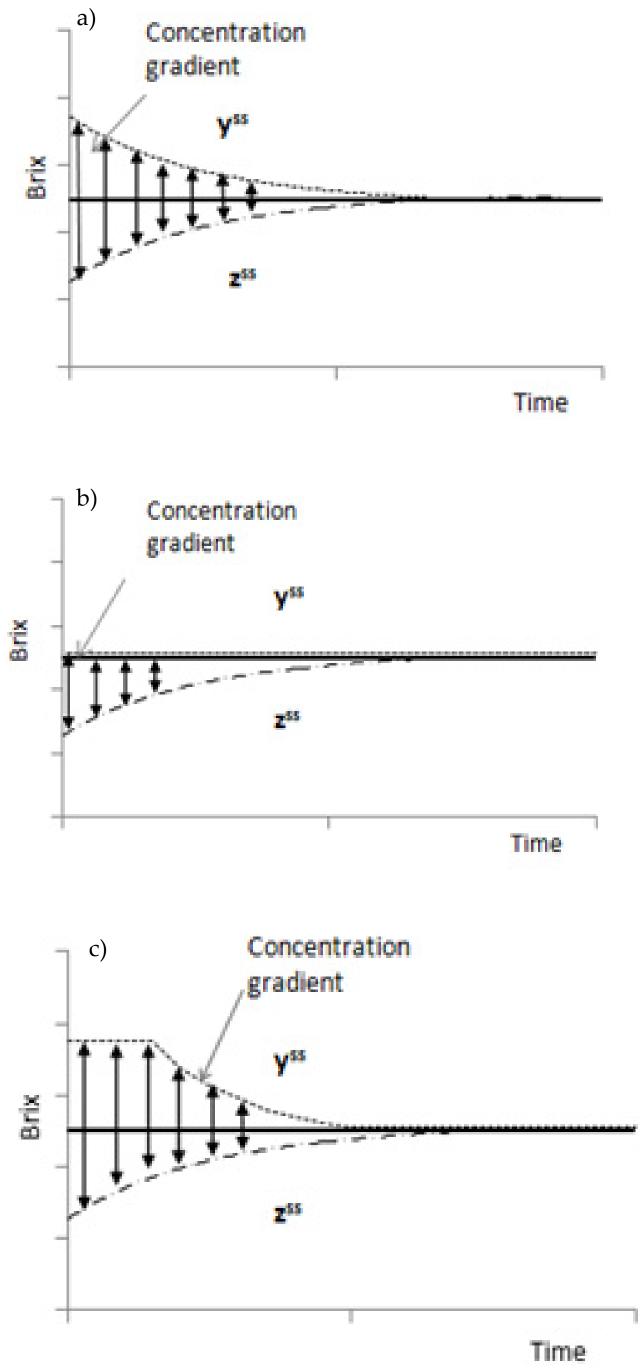

FIG 1: EVOLUTION OF SOLUBLE SOLIDS CONCENTRATION IN THE OSMOTIC MEDIUM (Y^{SS}) AND IN THE FRUIT LIQUID PHASE (Z^{SS}) UNDER THE DIFFERENT DEHYDRATION PROCESSES: WET OSMOTICDEHYDRATION WITHCONSTANTCONCENTRATION OF THE MEDIUM (WOD-C), WET OSMOTIC DEHYDRATION WITH VARIABLE CONCENTRATION OF THE MEDIUM (WOD-V) AND DRY OSMOTIC DEHYDRATION WITH VARIABLE CONCENTRATION OF THE MEDIUM (DOD-V).

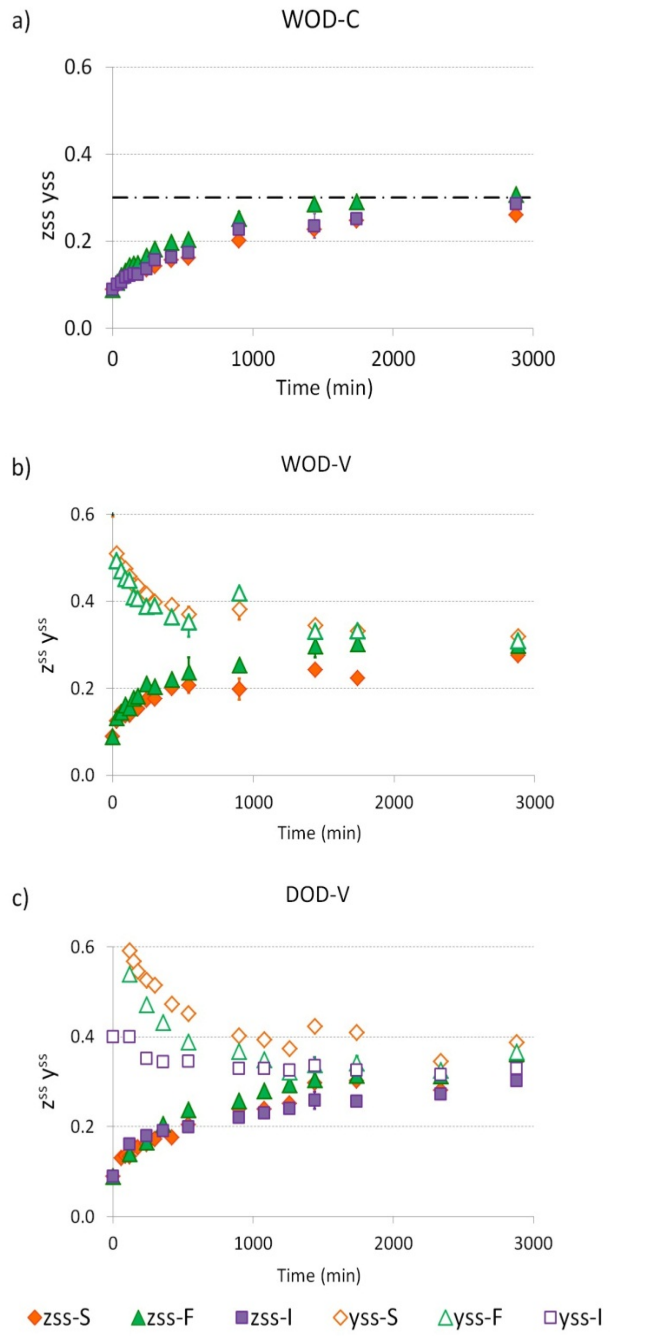

FIG. 2.EVOLUTION OF THE SOLUBLE SOLIDS CONCENTRATION IN THE MEDIUM (Y^{SS}) AND IN THE STRAWBERRY SAMPLES LIQUID PHASE (Z^{SS}) DURING THE DIFFERENT OSMOTICDEHYDRATION PROCESSES:WET OSMOTIC DEHYDRATION WITH CONSTANT CONCENTRATION OF THE MEDIUM (WOD-C), WET OSMOTIC DEHYDRATION WITH VARIABLE CONCENTRATION OF THE MEDIUM (WOD-V) AND DRY OSMOTIC DEHYDRATION WITH VARIABLE CONCENTRATION OF THE MEDIUM (DOD-V), FOR THE THREE SUGARS (S: SUCROSE; F: FRUCTOSE; I: ISOMALTULOSE).

On the other hand, it is observed that either the type of sugar or the type of process (wet or dry method) or the concentration of the medium influences the concentration rate of the liquid phase. For this reason, the evolution of the concentration of the fruit liquid phase under each of the studied conditions has been modelled using equation 2:

$$\frac{z_t^{ss}-z_0^{ss}}{z_\infty^{ss}-z_0^{ss}} = k_z \cdot t^{0.5} \qquad (2)$$

Where, z_t^{ss}: Concentration of the soluble solutes in the liquid phase at each treatment time (g soluble solids/g liquid phase); z_0^{ss}: Initial concentration of the soluble solutes in the liquid phase (g soluble solids/g liquid phase); z_∞^{ss}: Equilibrium concentration of the soluble solutes in the liquid phase (g soluble solids/g liquid phase); k_z: Kinetic parameter ($min^{0.5}$); t: Treatment time (min).

Table 1 illustrates the values of the kinetic parameter as well as the equilibrium time estimated using equation 2. The concentrating rate of the liquid phase is higher when the concentration of the external medium is variable, the wet process slightly superior to the dry process. As referred to the type of solute, it can be said that the smaller the molecular size and the higher the solubility are, the greater the depressing capacity of water activity is, which results in faster concentration kinetics in the liquid phase.

TABLE 1.KINETIC PARAMETER (K_Z) FROM THE LIQUID PHASE CONCENTRATION MODEL AND THE ESTIMATED EQUILIBRIUM TIME (T (MIN)).

Sugar			S	F	I
WET	C[1]	k_z	0.016	0.024	0.018
		t	3810	1736	3156
		R^2	0.98	0.99	0.97
	V[2]	k_z	0.025	0.032	-
		t	1626	965	-
		R^2	0.96	0.96	-
DRY	C[1]	k_z	0.023	0.027	0.020
		t	1842	1324	2268
		R^2	0.98	0.98	0.92

[1] C: Constant; [2] V: Variable

Net Fluxes of Mass, Water and Solutes

The evolution of the previously described liquid phase concentration provides interesting information from a thermodynamic point of view but insufficient when evaluation of other aspects related to mass transfer is required (Fito & Chiralt, 1997). Therefore, the analysis of the net fluxes of mass, water and solutes can be used to improve this comparative study, since the same liquid phase concentration can be achieved with different combinations of water loss and solute gain

with important implications for the process yield and product characteristics (Pani et al., 2008).

Figure 3 shows the corresponding net fluxes of mass, water and solutes for the different studied conditions.

The obtained results indicate that the conditions in the medium (constant or variable concentration, wet or dry process) do not determine the maximum flux values (maximum soluble solids gain and water and total mass loss); the average concentration gradient between the fruit and the medium is the variable that determines the maximum net fluxes of mass, water and solutes. The higher the average concentration gradient is, the higher the water loss and the lower the gain in solutes are. Therefore, in the experiments performed with isomaltulose hardly any differences were seen; probably because the maximum concentration of the solution generated in the dry process is near to the concentration of the solution used in the wet process.

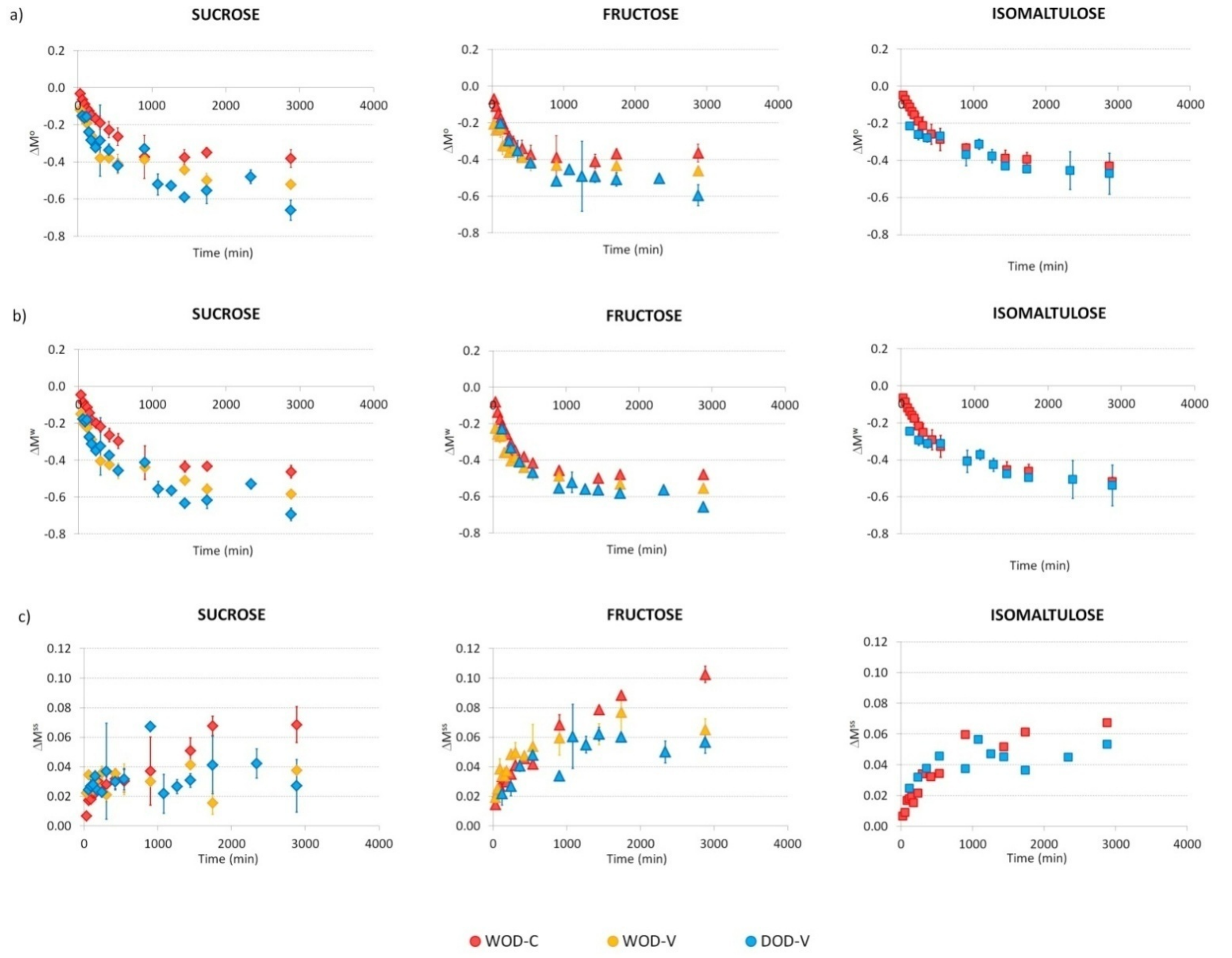

FIG.3. NET FLUXES OF MASS (ΔM^o), WATER (ΔM^w) AND SOLUTES (ΔM^{ss}) EXPERIMENTED BY THE STRAWBERRY SAMPLES DURING THE DIFFERENT OSMOTIC DEHYDRATION PROCESSES: WET OSMOTIC DEHYDRATION WITH CONSTANT CONCENTRATION OF THE MEDIUM (WOD-C), WET OSMOTIC DEHYDRATION WITH VARIABLE CONCENTRATION OF THE MEDIUM (WOD-V) AND DRY OSMOTIC DEHYDRATION WITH VARIABLE CONCENTRATION OF THE MEDIUM (DOD-V), FOR THE THREE SUGARS(S: SUCROSE; F: FRUCTOSE; I: ISOMALTULOSE).

Furthermore, in the experiments carried out with sucrose or fructose, the maximum concentration gradient is achieved in the dry process due to the higher solubility of these sugars, which results in maximum levels of water fluxes.

Additionally, the net fluxes of mass, water and solutes were also modelled according to equation 3:

$$\Delta M_t^i = K_j \cdot t^{0.5} \quad (3)$$

Where, ΔM: Net Flux variation; K: Flux kinetic parameter ($min^{0.5}$); t: Process time (min). Super indexes i and j: (o= mass; w= water; ss= soluble solids).

Table 2 shows the values of the kinetic constants obtained for the different studied conditions.

TABLE 2. VALUES OF THE KINETIC PARAMETER (KJ) FOR THE PREDICTION OF MASS, WATER AND SOLUBLE SOLIDS FLUXES CONCERNING THE DIFFERENT DEHYDRATION PROCESSES (WOD-C) WET OSMOTIC DEHYDRATION WITH CONSTANT CONCENTRATION OF THE MEDIUM, (WOD-V) WET OSMOTIC DEHYDRATION WITH VARIABLE CONCENTRATION OF THE MEDIUM AND (DOD-V) DRY OSMOTIC DEHYDRATION WITH VARIABLE CONCENTRATION OF THE MEDIUM, FORTHE THREE STUDIED SUGARS (S: SUCROSE; F: FRUCTOSE; I: ISOMALTULOSE).

Sugar	**WOD**				**DOD**	
	Medium Conditions				Medium Conditions	
	CONSTANT		VARIABLE		VARIABLE	
	K^o	R^2	**K^o**	R^2	**K^o**	R^2
S	-0.011	0.97	-0.019	0.97	-0.018	0.94
F	-0.017	0.99	-0.022	0.80	-0.018	0.99
I	-0.011	0.98	-	-	-0.012	0.85
	K^w	R^2	**K^w**	R^2	**K^w**	R^2
S	-0.012	0.98	-0.021	0.97	-0.020	0.95
F	-0.019	0.99	-0.025	0.83	-0.020	0.98
I	-0.014	0.99	-	-	-0.015	0.85
	K^{ss}	R^2	**K^{ss}**	R^2	**K^{ss}**	R^2
S	0.0017	0.87	0.0023	0.91	0.0019	0.71
F	0.0021	0.99	0.0053	0.80	0.0020	0.98
I	0.0015	0.92	-	-	0.0020	0.99

These kinetic parameters also indicate that mass transfer is quicker under conditions with variable concentration of the medium. Besides, when osmotic dehydration takes place in the wet process, the kinetics are slightly superior, in spite of the fact that in the dry process the average concentration gradient is greater. These results could be related to a greater collapse of the cellular structure at the interphase during the osmotic dry processes (DOD).

It can be observed that the higher capacity for depressing the water activity of fructose could explain the higher values of the kinetic parameters of water loss (K^w), while the solubility and the molecular size of the osmotic agent are the main factors affecting the kinetics of the gain in soluble solutes (K^{ss}).

Conclusions

Mass transfer kinetics are higher when the concentration of the external medium is variable, slightly higher in the wet processes than the dry ones. The concentration of the medium (constant or variable), and the type of process (wet or dry) do not determine the maximum flux values. The variable that determines the maximum net fluxes of mass, water and solutes is the average concentration gradient between the fruit and the medium. In order to optimize the osmotic dehydration process, not only the aspects related to the transport kinetics of the medium described in this work must be taken into account, but also aspects of the final quality of the products obtained, as well as the advantages and disadvantages of each of the methods, considering handling and the environment.

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